Mapping Entanglement In and Out of Quantum Memories

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Abstract: We report entanglement generation in atomic quantum memories via deterministic mapping of photonic entanglement. The atomic entanglement is retrieved back into photon modes after a programmable storage time, with an overall efficiency of 17%.

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Development of scalable quantum networks requires the capabilities to create, store, and distribute entanglement among distant memory nodes via photonic channels [1, 2]. Significant progress has been made based on quantum memories consisting of a large ensemble of identical atoms. In deterministic schemes, storage and retrieval have been demonstrated for single photon pulses [3, 4], but not for entangled states. Based on probabilistic protocols [5], it has been demonstrated mapping of single collective atomic excitations to single photons [6, 7, 8, 9], entanglement of two distant ensembles [10], entanglement distribution that enables quantum cryptography [11] and light-matter teleportation [12]. However, due to the probabilistic nature, higher fidelity of heralded entanglement necessarily requires lower probability of state preparation, and consequently longer measurement time and more stringent noise reduction. This limitation hinders the potential scalability of these protocols [13]. Here, we demonstrate a protocol which overcomes this intrinsic drawback by separating the processes of entanglement generation and storage and thus enables efficient scaling for high-fidelity quantum communication.

In our protocol, we first split a single photon into two modes to create photonic entanglement [14]. Via dynamic Electromagnetically Induced Transparency (EIT) [15, 16], we coherently map the entangled photon state to an entangled matter state. After a programmable delay, the matter entanglement is mapped back into photon modes. Entanglement of the input and output photon states can be explicitly verified.

Our single photon source is based on Raman transitions in an optically thick cesium ensemble [5, 17]. Single photons of 28 ns-long are generated in a heralded fashion, resonant with the $6S_{1/2}, F = 4 \leftrightarrow 6P_{3/2}, F' = 4$ transition. Relative to a coherent state, we achieve a two photon component suppression of 11 ± 4. A beam displacer splits the single photon into two modes with orthogonal polarizations, called L_{in} and R_{in}, which forms an entangled photonic state $|\phi\rangle_{sig} = \frac{1}{\sqrt{2}}(|0_{L_{in}}\rangle|1_{R_{in}}\rangle + e^{i\phi_{rel}}|1_{L_{in}}\rangle|0_{R_{in}}\rangle)$.

The quantum memories, called L_a and R_a, are two ensembles of cesium atoms in a magneto-optical trap, located in a vacuum chamber 3 meters away from the single photon source. L_a and R_a are prepared in the state $|F = 4, m_F = 0\rangle$ via optical pumping. Upon the arrival of $|\phi\rangle_{sig}$, strong control fields $\Omega_c^{(L,R)} = 24$ MHz (resonant with the $6S_{1/2}, F = 3 \leftrightarrow 6P_{3/2}, F' = 4$ transition) first open transparency windows in L_a and R_a and compress $|\phi\rangle_{sig}$ within the ensembles. Then, by turning off $\Omega_c^{(L,R)}$, $|\phi\rangle_{sig}$ is coherently transferred into collective atomic excitations. This mapping entangles L_a and R_a. After a chosen storage time of 1.1 μs, the atomic state is converted back into photon fields by switching on $\Omega_c^{(L,R)}$. We measure an overall storage and retrieval efficiency of $17 \pm 1\%$, in agreement with numerical simulations based on [16]. The memory time of the ensembles are ~ 8 μs.

Verification of the entanglement is performed on the input and output photonic states. Following Ref. [10], we first obtain a lower bound of entanglement by reconstructing a reduced density matrix ρ for L_k and R_k, $k \in \{in, out\}$, in the photon-number basis $|n_L, m_R\rangle$. ρ is constrained to a subspace $\{n, m\} = \{0, 1\}$, and we assume coherence only between $|1_L 0_R\rangle_k$ and $|0_L 1_R\rangle_k$. Then entanglement is quantified by concurrence $C = \frac{1}{P} max(0, 2|d| - 2\sqrt{p_{00}p_{11}})$ [18]. p_{ij} is the probability to find i photons in mode L_k and j in mode R_k, $P = p_{00} + p_{10} + p_{01} + p_{11}$, and d is the non-vanishing off-diagonal term of ρ. To obtain p_{ij}, we perform separate single-photon detections on L_k, R_k, and correct for the independently measured propagation and detection losses of the fields after the ensembles. To measured d, we first rotate the polarizations of L_k, R_k to combine them at a polarizing beam splitter, and then add a variable phase to L_k to produced interference fringes at the detectors with visibility V. From V we calculate $d \simeq \frac{V(p_{10}+p_{01})}{2}$.

The measured interference fringes and the reconstructed density matrices are shown in Fig. . The results give concurrence $C_{in} = 0.10 \pm 0.02$ and $C_{out} = (1.9 \pm 0.4) \times 10^{-2}$ for the input and output photon states, respectively. Since the mapping of L_a, R_a into L_{out}, R_{out} is a local operation, C_{out} gives a lower bound for the entanglement

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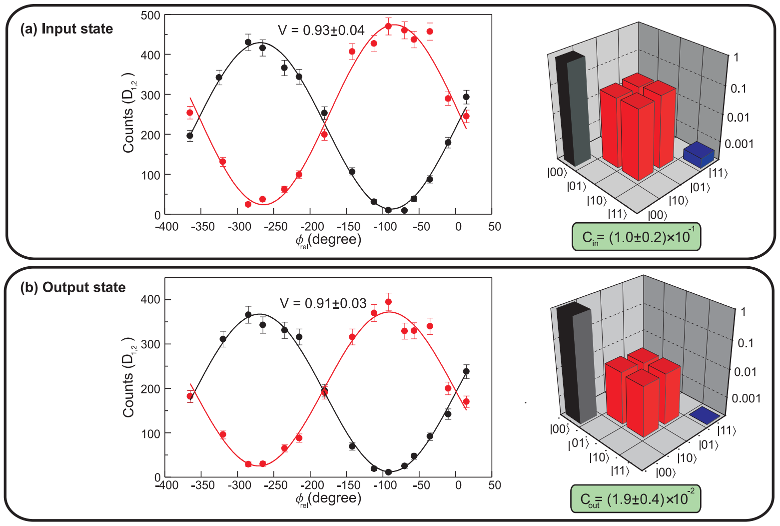

Fig. 1: Entanglement for the optical modes at the (a) input and (b) output of the quantum memories. Left panels show the interference fringes when the relative phase between the two optical modes are varied. Right panels show the reconstructed density matrices in log scales. The estimated concurrence is given in each case. Each point of the fringe is taken for 20,000 (100,000) heralding events for the input (output) state. Error bars indicate statistical errors.

between L_a and R_a. Thus, we demonstrate the reversible mapping of photonic entanglement to and from quantum memories.

Our current results are limited by the large vacuum component of our available single photon source, which reduces the degree of entanglement in the input, and the retrieval efficiency of the EIT process, which bounds the entanglement transfer to $C_{out}/C_{in} = (20 \pm 5)\%$. With improved retrieval efficiency and memory time, along with the rapid development of on-demand single photon sources [19], the demonstrated quantum interface for entanglement will enable deterministic entanglement generation and distribution among quantum memories for scalable quantum networks.

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